

Sizing a solar dish Stirling micro-CHP system for residential application in diverse climatic conditions based on 3E analysis



Ramin Shabanpour Moghadam^b, Hoseyn Sayyaadi^{a,*}, Hadi Hosseinzade^a

^a Faculty of Mechanical Engineering-Energy Division, K.N. Toosi University of Technology, P.O. Box: 19395-1999, No. 15-19, Pardis Str., Mollasadra Ave., Vanak Sq., Tehran 1999 143344, Iran

^b Department of Mechanical and Energy Engineering, Power and Water University of Technology, Tehranpars, Tehran, Iran

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ABSTRACT

A solar dish Stirling cogeneration system is considered to provide energy demands of a residential building. As energy demands of the building and output power of the engine are functions of weather condition and solar irradiation flux, the benchmark building was considered to be located in five different cities in Iran with diverse climatic and solar irradiation conditions. The proposed solar dish Stirling micro-CHP system was analyzed based on 3E analysis. The 3E analysis evaluated primary energy saving analysis (energy analysis), carbon dioxide emission reduction (environmental analysis) and payback period for return of investment (economic analysis) and was compared to a reference building that utilized primary energy carriers for its demands. Three scenarios were considered for assessment and sizing the solar dish Stirling engine. In the first scenario, size of the solar dish Stirling engine was selected based on the lowest annual electric power demand while, in second, the highest annual electric power consumption was considered to specify size of the engine. In the third scenario, a solar dish Stirling engine with constant output capacity was considered for the five locations. It was shown that implementing the solar dish Stirling micro-CHP system had good potential in primary energy saving and carbon dioxide emission reduction in all scenarios and acceptable payback period for return of the investment in some scenarios. Finally, the best scenario for selecting size of the engine in each city was introduced using the TOPSIS decision making method. It was demonstrated that, for dry weather, the first scenario was the best while, for hot and humid cities and temperate and humid places, the second and third scenarios were the best options, respectively.

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1. Introduction

In the last half century, global energy consumption has been increased very rapidly and its growth is expected to continue over the next 50 years. World market energy consumption is projected to increase by 44 percent from 2006 to 2030 [1]. Solar power is one of the fastest growing sources of the renewable energy worldwide. Conversion of solar energy into electric power and/or thermal energy for heating/cooling leads to significant reduction in primary energy consumption and greenhouse gas emission, especially in large scale applications.

Solar thermal power systems use the heat produced by collectors which concentrate solar energy on the focal point of the collector in order to heat up a working fluid in a heat engine/generator to produce power. Among three technologies of solar thermal power such as tower, trough and dish, dish Stirling systems have demon-

strated the highest efficiency [2]. For solar electric generation in the range of 1–100 kWe, Stirling engine is considered to be the cheapest one [3]. Although efficiency of Stirling engine may be low, reliability is high and cost is low. Moreover, simplicity and reliability are the keys to a cost-effective Stirling solar generator [3]. Kong et al. [4] presented an energy and economic feasibility analysis of a tri-generation unit using Stirling engine that utilized waste heat. They found that this CCHP unit could save more than 33% of primary energy compared to a conventional stand-alone system.

Abbas and Boumeddane [5] performed technical and economic analysis on a 100 MWe solar dish Stirling farm in three different sites. They concluded that leveled cost of the energy varied in the range of 11.55–23.55 C\$ kW h⁻¹ depending on the location. Paepe et al. [6] performed an investigation of the micro-CHP using three different technologies including gas engine, fuel cell and Stirling engine. They realized that all CHP installations, if well-sized, could lead to reduction in primary energy saving and carbon dioxide emission. They also showed that gas engines had the best performance. Furthermore, their economic analysis demonstrated that

* Corresponding author. Tel.: +98 21 8406 3212; fax: +98 21 8867 4748.

E-mail addresses: Ramin.Shabanpour2005@gmail.com (R.S. Moghadam), sayyaadi@kntu.ac.ir, hoseynsayyaadi@gmail.com (H. Sayyaadi).

Nomenclature

A	area (m^2)	T	temperature (K)
C	purchased cost (US \$)	<i>Greek symbols</i>	
c	energy unit cost (US \$ kW h^{-1})	η	efficiency, useful output divided by input amount
CDE	carbon dioxide emissions (kg h^{-1}) or (kg year^{-1})	<i>Subscripts</i>	
$CDER$	carbon dioxide emissions reduction	b	boiler
DNI	direct normal irradiation	BL	book life
$\dot{E}$	electric power (kW)	c	cooling
$\dot{E}_b$	electric power used by hot water boiler (kW)	cc	cooling coil
$\dot{E}_{ch}$	electric power used by absorption chiller (kW)	ch	absorption chiller
f	supplied fuel energy (kW h)	$COLEC$	collector
$HVAC$	heating, ventilating and air conditioning	$grid$	electricity supplied by grid
$H.W.B$	hot water boiler	hc	heating coil
NG	natural gas	hw	hot water
$\dot{Q}$	thermal energy (kW)	hws	domestic hot water
$\dot{Q}_{cc}$	thermal energy delivered to cooling coils (kW)	irr	sun irradiation
$\dot{Q}_{ch}$	thermal energy required for generator of absorption chiller (kW)	$H.E$	heat exchanger
$\dot{Q}_{hc}$	thermal energy delivered to heating coils (kW)	L	levelized
$\dot{Q}_{LS,b}$	thermal energy lost from hot water boiler (kW)	LS	heat loss
$\dot{Q}_{LS,D.W.H1}$	thermal energy lost from D.W.H 1 (kW)	r	heat recovery
$\dot{Q}_{LS,D.W.H2}$	thermal energy lost from D.W.H 2 (kW)	rec	heat received from the sun
$\dot{Q}_{LS,H.E1}$	thermal energy lost from H.E 1 (kW)	req	electric energy demand
$\dot{Q}_{LS,S.E}$	thermal energy rejected from the cold-end of Stirling engine (kW)	SE	Stirling engine
$\dot{Q}_r$	thermal energy recovered at the cold end of Stirling engine (kW)	$sold$	electricity sold to grid

fuel cells were too expensive in comparison to gas engines which had small rate of return for capital investment. From the economic aspect, installing a CHP in a residential building is not interesting because of the high capital cost and long period for return of the capital investment. However, it is required to mention that their Stirling engine is an externally gas burned system. Among four main primary movers of the micro-CHP system including internal combustion engine, micro-gas turbine, fuel cell and Stirling engine, there is only Stirling engine that can be integrated to the solar energy. Therefore, it is expected to have more primary energy saving and more significant reduction in greenhouse gas emission in the case of CHP system with solar dish Stirling primary mover. Nosek [7] introduced a new 10 kWe hybrid solar dish Stirling which was used in micro-CHP applications. They applied a natural gas burner to heat up the Stirling engine's hot-end when electric output of the system was lower than 10 kWe during 24 h of the system operation in the hybrid mode. Results showed that the annual amount of primary energy consumption decreased to 49 MW h. Also, the total amount of annual energy saving in the solar mode was 50.38 MW h, which was equivalent to 4800 m^3 of the natural gas consumption in the conventional gas burner. Li et al. [8] performed a real test on a Stirling engine driven by exhaust waste gas. Their test results showed that the output shaft power could reach 3476 W at shaft speed of 1248 RPM. It means that, the Stirling engines driven by mid-high temperature waste gases were capable of achieving valuable power for engineering applications. Bravo et al. [9] made a comparison in terms of environmental effect between a photovoltaic power generation system and a dish-Stirling technology based on CO_2 -equivalent emissions. The results demonstrated that level of environmental impacts was similar for both technologies. Magri et al. [10] investigated an energetic and environmental analysis on a typical micro-CHP driven by a natural gas fired Stirling engine. Then, operation of the mentioned plant was compared with that of the condensing boiler to meet heating demands. The result showed that the micro-CHP unit can provide

reduction in the primary energy demand with respect to a conventional boiler (−27.3%) and also with respect to a condensing gas boiler (−9.1%). Furthermore, they concluded that utilizing micro-CHP unit may lead to remarkable reduction of CO_2 emission. Harrod et al. [11] performed an analysis on biomass-fired Stirling engine in order to determine how an individual component of the micro-CHP system such as prime mover, heat recovery system, auxiliary boiler, absorption chiller and heating unit coil affect the system's primary energy consumption (PEC) and operational cost. They recommended engine size of 8 kW as the best choice so as to achieve the best cost of system applied for the 511 m^2 area facility located in Atlanta. There are a lot of valuable investigations in line with 3E analysis. Mago and Chamra [12] performed an analysis and optimization on a typical CCHP system considering energy and economic and environmental aspects. They introduced three criteria which were primary energy saving (PE), emission reduction (ER) and operational cost (OC) for optimization of their plant. Also, they applied three operational strategies following electric load (FEL), following thermal load (FTL) and hybrid electric thermal load (HETS) for performance evaluation of their proposed system. In order to obtain a better view of optimized value, the authors compared their CCHP system with a reference building which used a conventional HVAC system for meeting energy demands of the simulated building. The results explicated that, for the evaluated cities, the best optimization criterion was PE-O (primary energy optimization) because of minimizing value of PEC while decreasing values of cost and CDE. Cho et al. [13] implemented an assessment on CCHP systems based on operational cost, primary energy consumption and carbon dioxide emission using different cities with various climatic conditions. Their results showed that CCHP systems augmented the site energy consumption (SEC) with respect to the reference building. Results for various site locations clarified the fact that there was not a common trend among three optimization criteria which were primary energy optimization (PE-O), cost optimization (Cost-O) and carbon dioxide emission optimization

(CDE-O). This can be attributed to the variation of building energy loads, electricity and fuel costs and CO₂ emission factor for the evaluated cities. Alanne et al. [14] performed an evaluation and optimization of Stirling engine in a micro-CHP system for a residential building. They searched an optimally operated configuration for integration of a Stirling engine-based micro-CHP system in a residential building by comparing performance of various systems and strategies of a reference system. The results demonstrate that an optimally operated micro-CHP including heat recovery and suitable thermal storage would result in 3–5% reduction in primary energy consumption and CO₂ emissions when compared to a conventional hydronic heating system. Furthermore, their suggested system ensured creating annual saving in all combinations of electricity and fuel price of between 0.05 and 0.15 € kW h⁻¹. Dorer and Weber [15] carried out an energy and CO₂ assessment of residential micro-CHP system using a transient model in TRNSYS simulation program. In order to find the best cogeneration technology in terms of primary energy saving and CO₂ emission, various CHP technologies such as natural gas fueled solid oxide (SOFC), polymer electrolyte membrane fuel cells, Stirling and internal combustion engines were taken into account. The results were compared with a conventional building which used a natural gas-fired boiler and electricity from grid to meet energy demands of the building. Also, a ground-coupled heat pump system was analyzed for further comparison. The analysis demonstrated that the maximum reduction of non-renewable primary energy with the evaluated cogeneration system was 14%. In the case of CO₂-eq emissions, most cogeneration systems offered reduction in the case of using European electricity mix (up to 22%). For the case of electricity generation by combined cycle power plant, maximum CO₂-eq emission reduction was resulted in heat pump systems (up to 29%). Moreover, the maximum decrease of CO₂-eq emission was obtained in the internal combustion engine when being applied in a single-family house. E. Cardona et al. [16] performed 3E analysis and optimization on internal combustion engine-driven CCHP integrated to a reversible heat pump. The obtained results indicated that a complete matching between “economic” and “energy-environmental” choices was not feasible because of requiring “ad hoc” measures for each case study.

In this paper, a typical solar dish Stirling unit was integrated by an HVAC system to meet electric, heating, cooling and hot water demands of a typical 5-storey residential building. A benchmark building was assumed to be located in five different cities with diverse climatic conditions (including temperate and dry, cold and dry, hot and humid, temperate and humid and hot and humid weathers) to obtain different electric, heating, cooling and hot water load profiles. The proposed CHP system was evaluated based on 3E analysis. The 3E analysis considers energy, environmental and economic analysis simultaneously. An energy analysis was performed to illustrate benefits of the proposed system. With calculating site-source energy conversion factor for electricity and natural gas, the primary energy saving (PES) was obtained for the plant. Moreover, by calculating a factor that represented carbon dioxide emission (namely, carbon dioxide emission factor), ability of the proposed CHP system for reducing the carbon dioxide emission was assessed in the aforementioned five different climatic conditions. Furthermore, the economic analysis based on the total revenue requirement (TRR) method was performed to evaluate payback period for return of investment used for providing CHP system. Energy, environmental and economic analysis of the proposed micro-CHP system with a dish Stirling prime mover was performed in three scenarios. In the first scenario, size of dish Stirling engine in each city was selected based on the minimum annual electric load. In this scenario, difference between the actual electricity demand and output electric power of the solar dish Stirling engine was assumed to be delivered by the grid electricity. In the

second scenario, the prime mover was sized based on the highest annual electric power demand. In the third scenario, a Stirling engine with constant output power capacity of 10.0 kW at maximum solar irradiation (1000 W m⁻²) was utilized for the proposed CHP system in each city. Finally, the best option for sizing the prime mover of the CHP system in each location was suggested using TOPSIS decision making method.

2. System description

A micro-CHP system with solar dish Stirling engine as prime mover as indicated in Fig. 1a was considered for providing electric, heating and cooling demands of a residential building. This micro-CHP system was considered to support electric, heating and cooling loads of a benchmark 5-story 10-flat residential building. The building was aligned with north with the total living area of 960 m². Complimentary information regarding the proposed building is given in Fig. 1b and c and Table 1.

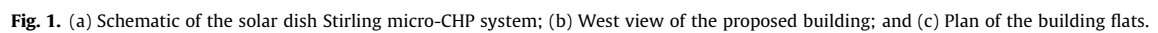
A hot water natural gas boiler (H.W.B) and a single effect absorption chiller (S.E.A.C) were utilized to supply heating and cooling demands of the building. Moreover, a typical free-piston Stirling engine integrated to a solar concentrator was provided to supply a part of electricity demand. The rest of electricity demand was provided by the local grid in the case that electricity demand of the building was larger than the output power capacity of the engine. A jacket heat exchanger (H.E 2) recovered rejected heat at the cold-end of Stirling engine. This recovered heat was absorbed by the engine's cooling water in a heat exchanger, namely D.W.H 1, in Fig. 1a; hence, it preheated the inlet cold tap water (from city water network) used for providing the hot water demand. The preheated water came from the D.W.H 1 flows through another heat exchanger (D.W.H 2), which was warmed up by the hot water boiler. If output power of dish Stirling system was higher than the electricity demand, the excessive electricity was sold to electricity grid. Furthermore, as is observed in Fig. 1a, hot water boiler provided heating demand of the building through heat exchanger H.E 1 and heating coils located inside the building (nominated as H.C in Fig. 1a). Moreover, H.W.B provided heating load of the generator of a single effect absorption chiller (S.E.A.C). The S.E.A.C provided cooling demands of the building through the room cooling coils (C.C).

3. Modeling

3.1. Estimating energy demand

Energy demand of the building highly depended on climatic conditions. In order to evaluate effectiveness of the proposed micro-CHP system with the solar dish Stirling engine as prime mover for reducing primary energy consumption and carbon dioxide emission when utilized in various climatic conditions, five cities in Iran with diverse climatic conditions were selected to obtain annual profiles of buildings' electric, heating and cooling loads. These cities were Tehran (selected as the representative of temperate and dry weather), Tabriz (selected as the representative of cold and dry weather), Bandar Abbas (selected as the representative of hot and humid weather), Rasht (selected as the representative of temperate and humid weather) and Yazd (selected as the representative of hot and dry weather). Climatic outdoor design conditions of these cities are indicated in Table 2.

To calculate buildings' heating and cooling loads, the proposed benchmark residential building was simulated in Carrier-HAP3.4 software (heating load also included domestic hot water load). Electricity demand of the reference building was classified to two categories including variable and fix loads. Variable loads denoted



considered the fixed loads. It is momentous to mention that fix loads refer to electric loads that do not vary through the seasons of the year. As a matter of fact, they can change from 1 h to another

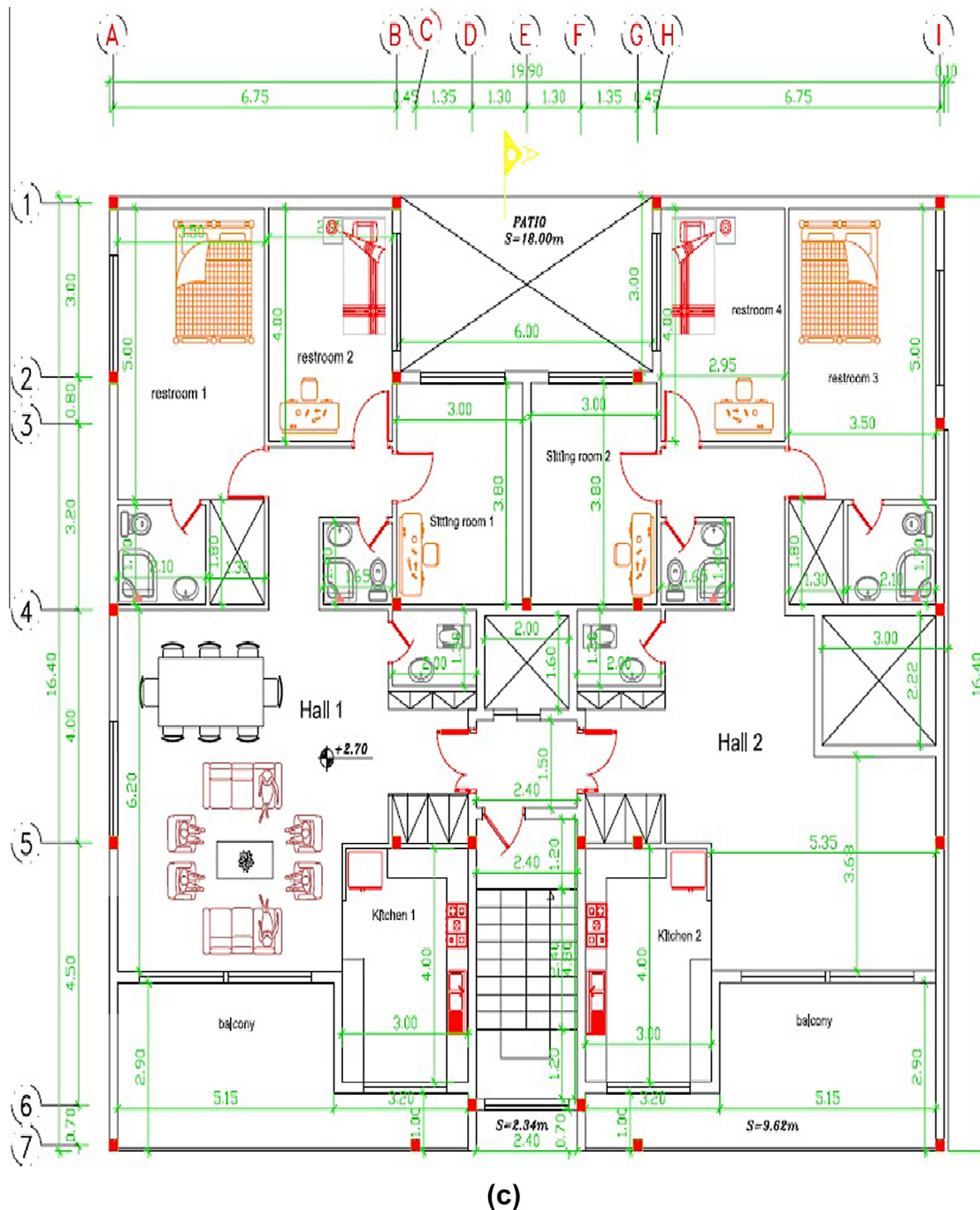


Fig. 1 (continued)

during a day. All appliance loads, except refrigerator load, were deemed as fix loads. Electric loads consumed by HVAX equipment were obtained from vendors catalogues of these equipment. Table 3 shows the electric appliances assumed to be used in each flat of the building. Figs. 2–4 demonstrate heating, cooling and electricity load profiles of the proposed benchmark building, respectively. In these figures, the magnitudes assigned to each month were an hourly average through 24 h per day multiplied by the number of days in a month.

3.2. Energy analysis of solar dish Stirling engine

According to the BSR company record in EPRI report [17], real efficiency of their typical solar powered Stirling engine was re-

ported as 50% of the Carnot efficiency. The Carnot efficiency is calculated as:

$$\eta_{Carnot} = 1 - (T_c/T_h) \quad (1)$$

where η_{Carnot} is Carnot efficiency of the Stirling engine, T_c is temperature at the cold-end of the Stirling engine (K) and T_h is temperature at the hot-end of the Stirling engine (K). T_c is assumed equivalent to the ambient temperature. In order to estimate hot-end temperature in different solar irradiation, $T_h = 800^\circ\text{C}$ was considered at maximum DNI = 1000 W m^{-2} [18] and, with a simple proportion with various DNIs for the selected cities (Fig. 5), values of T_h were determined as indicated in Table 4. Also, values of the ambient temperature (T_a) are given in Table 5. Values of the estimated real efficiency of the Stirling engine in the proposed cities during a year

Table 1

Description of the simulated building in Carrier, HAP 3.4.

Orientation	Aligned with north
Building type	Residential apartment
Number of floor	5
Number of flats in each floor	2
Area of each flat	96.0 m ² (7.1 m × 13.5 m)
Average ceiling height	3.0 m
External wall overall <i>U</i> -value	2.179 (W/m ² K)
Internal wall overall <i>U</i> -value	2.839 (W/m ² K)
Windows overall <i>U</i> -value	3.591 (W/m ² K)
Roof overall <i>U</i> -value	0.684 (W/m ² K)
Floor overall <i>U</i> -value	0.454 (W/m ² K)
Total occupants	40
Total glass area	120 m ²

are presented in Table 6. Using Iran's meteorological data [19], the number of hours during which there was solar irradiation during each month of the year was obtained and used to calculate primary energy saving and carbon dioxide emissions reduction, represented in Sections 2.5 and 2.6, respectively. These data are presented in Table 7.

The power generated by the solar dish Stirling engine can be estimated based on the following expression:

$$\dot{E}_{SE} = RF \cdot HLF \cdot A \cdot \eta_{SE} \cdot \dot{Q}_{Solar,irr} \quad (2)$$

where η_{SE} is thermal efficiency of the Stirling engine as indicated in Table 6 and $\dot{Q}_{Solar,irr}$ is solar direct normal irradiation (W m⁻²) as indicated in Fig. 6. Moreover, in Eq. (2), $\dot{E}_{SE}$, RF and HLF are real output electric energy of the Stirling engine, reflectance factor for the solar dish Stirling system [7] and heat loss factor of the solar dish Stirling system [7], respectively. Values for RF and HLF were considered 0.90 and 0.74, respectively. A in Eq. (1) is the area of the solar dish. The output power as the nominal size of the solar dish was specified in three scenarios in this research:

- **Scenario I:** In this scenario, solar dish Stirling engine was sized based on the base electricity demand (minimum annual electric power demand) in the electric load profile (Fig. 4). Therefore, in this scenario for each location, a specific size of engine as indicated in Table 8 was obtained.
- **Scenario II:** In this scenario, solar dish Stirling engine was sized based on the maximum annual electric power demand (see Fig. 4). In this scenario for each location, a specific size of engine was obtained, as indicated in Table 8.
- **Scenario III:** An engine with fixed output power capacity was used in all locations (the proposed five cities). In this scenario, a solar dish Stirling engine with 10 kW nominal power obtained at maximum solar irradiation of 1000 W m⁻² was used as prime movers of the micro-CHP system in all the studied sites.

Moreover, the associated dish diameters for the considered sizes of Stirling engine in the selected cities are presented in

Table 3

List of the considered electric appliances in each flat of the building.

Electric appliance	Number in each flat of the building	Consumed power for each unit (W)
Iron	1	1000
LED television	1	150
Hair dryer	1	1000
Ventilation fan	2	30
Washing machine	1	500
Laptop computer	1	80
Freezer/refrigerator	1	350
Lightening lamp	8	30

Table 8. If output capacity of the dish Stirling system was not sometimes adequate to cover the whole electric demand, the difference between actual electricity demand and output electric power of the solar dish Stirling engine would be provided by the electricity local grid. Therefore, the following expression can be given:

$$\dot{E}_{grid} = \begin{cases} 0 & \text{when } \dot{E}_{SE} \geq \dot{E}_{req} \\ \dot{E}_{req} - \dot{E}_{SE} & \text{when } \dot{E}_{SE} < \dot{E}_{req} \end{cases} \quad (3a)$$

where $\dot{E}_{req}$ is electric power demand of the building (kW) and $\dot{E}_{grid}$ is purchased electric power from the local grid (kW).

Furthermore, in the case that electricity demand was less than the output capacity of the engine, the excess electricity was sold to the local grid.

$$\dot{E}_{sold} = \begin{cases} 0 & \text{when } \dot{E}_{SE} \leq \dot{E}_{req} \\ \dot{E}_{SE} - \dot{E}_{req} & \text{when } \dot{E}_{SE} > \dot{E}_{req} \end{cases} \quad (3b)$$

where $\dot{E}_{sold}$ denotes excess electricity sold to the local grid.

3.3. Energy analysis of the entire micro-CHP system

The total first law thermodynamic efficiency for the entire micro-CHP system was obtained from the following expression:

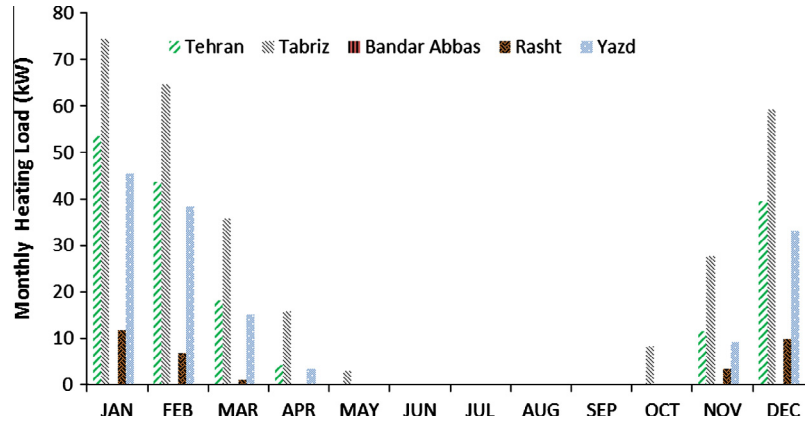
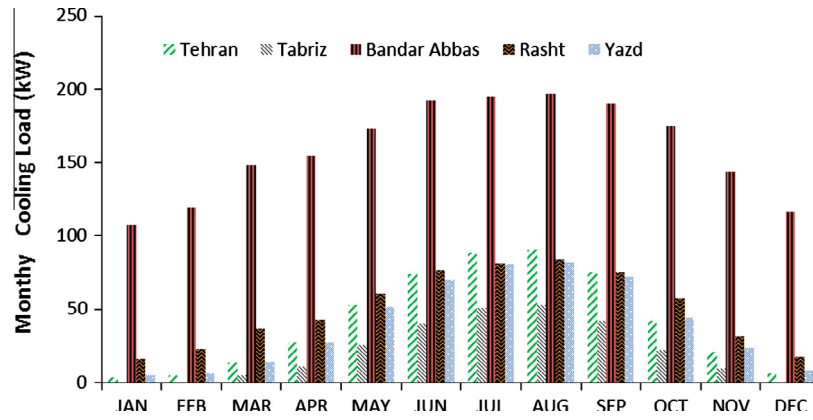
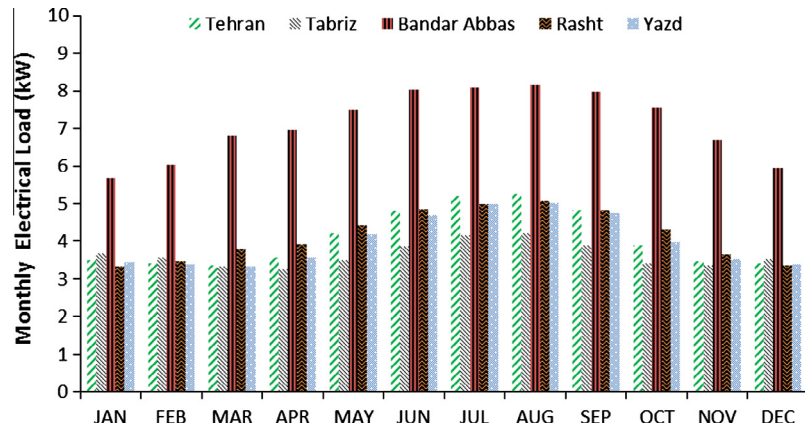
$$\eta_{overall,plant} = (\dot{Q}_c + \dot{Q}_h + \dot{Q}_{hw} + \dot{E}_{req}) / (\dot{Q}_{rec} + \dot{f}_b + \dot{E}_{grid} - \dot{E}_{sold}) \quad (4)$$

where $\eta_{overall,plant}$ is overall efficiency of the micro-CHP solar dish Stirling system. $\dot{Q}_c$, $\dot{Q}_h$, $\dot{Q}_{hw}$ and $\dot{E}_{req}$ are the building's cooling, heating, domestic hot water heating and electrical loads in kW, respectively. Moreover, $\dot{Q}_{rec}$, $\dot{f}_b$, $\dot{E}_{grid}$ and $\dot{E}_{sold}$ are the supplied solar heat to the hot-end of the Stirling engine (obtained from Eq. (5)) in kW, rate of fuel energy supplied to the hot water boiler (kW), purchased electric power from the local grid (kW) and electricity sold to the local grid (kW), respectively.

Table 2

Climatic data of the selected cities.

City	Weather category	Latitude (°N)	Longitude (°E)	Average annual relative humidity (%)	Summer design dry bulb (°C)	Winter design dry bulb (°C)	Summer design wet bulb (°C)	Winter design wet bulb (°C)
Tehran	Temperate and dry	35.7	51.4	40.1	38.9	−6.7	23.9	−8.8
Tabriz	Cold and dry	38.1	46.3	53.7	33.9	−10.8	18.0	−11.8
Bandar Abbas	Hot and humid	27.2	56.4	65	40.6	7.5	31.9	5.2
Rasht	Temperate and humid	37.2	50.2	71.3	31.9	−2.2	25.7	−2.9
Yazd	Hot and dry	31.9	54.4	31.4	40.0	−5.3	18.3	−7.3

Fig. 2. Monthly heating loads ($\dot{Q}_h$) for the selected cities.Fig. 3. Monthly cooling loads ($\dot{Q}_c$) for the selected cities.Fig. 4. Monthly electrical loads ($\dot{E}_{req}$) for the selected cities.

Terms in numerator of Eq. (4) are load data estimated and presented as loads' profiles in Figs. 2–4, respectively. $\dot{Q}_{rec}$ is obtained from the energy balance equation at the solar dish as follows,

$$\dot{Q}_{rec} = \dot{Q}_{sun,irr} \cdot A \cdot RF \cdot HLF \quad (5)$$

For $\dot{f}_b$ in Eq. (4):

$$\dot{f}_b = \frac{\dot{Q}_b}{\eta_b} \quad (6)$$

where $\dot{Q}_b$ and η_b are boiler heating capacity (kW) and thermal efficiency, respectively. Boiler efficiency along with specifications of some other HVAC equipment is presented in Table 9.

For estimation of the required capacity of the hot water boiler ($\dot{Q}_b$), a comprehensive first law thermodynamic analysis should be performed for the entire micro-CHP system. Complete list of energy balance equations for the entire micro-CHP plant is given in Table 10.

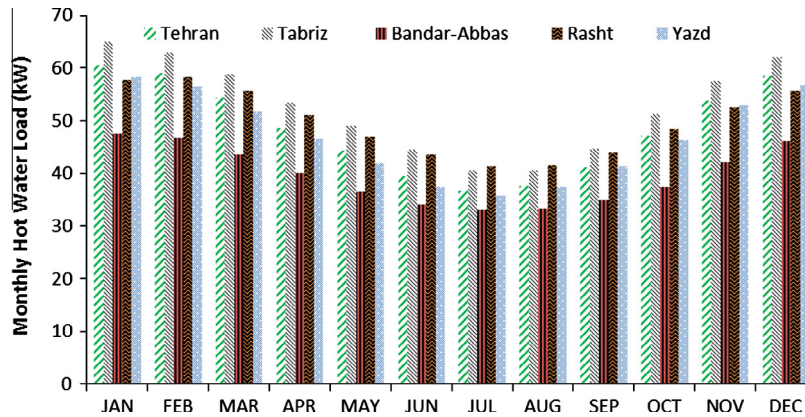


Fig. 5. Monthly hot water heating loads ($\dot{Q}_{hw}$) for the selected cities.

Table 4

The hot-end temperature (T_h) of the solar Stirling engine installed in the selected cities.

City	T_h (K)											
	January	February	March	April	May	June	July	August	September	October	November	December
Tehran	656.5	763.9	857.7	913.3	936.2	939.7	930.1	902.1	835.8	753.5	652.9	606.6
Tabriz	629.3	739.9	840.4	904.9	932.6	936.6	924.7	893.2	820.8	729.7	629.5	581.4
Bandar Abbas	759.0	848.3	924.5	956.4	960.8	955.3	949.3	940.9	906.1	842.7	759.9	721.7
Rasht	636.3	746.4	844.7	906.3	932.9	937.1	926.1	894.9	822.5	732.8	629.1	586.8
Yazd	702.6	802.9	886.7	934.7	949.7	947.4	938.0	920.0	870.2	795.8	703.3	659.3

Table 5

Values of the ambient temperature (T_a) for the selected cities.

City	T_a (K)											
	January	February	March	April	May	June	July	August	September	October	November	December
Tehran	276.3	278	283.3	289.8	294.7	300.0	303.3	302.2	298.3	291.4	284	278.6
Tabriz	271.4	273.6	278.3	284.3	289.3	294.5	298.9	298.8	294.3	286.9	279.7	274.6
Bandar Abbas	291.1	292	295.5	299.5	303.5	306.2	307.2	307.0	305.2	302.4	297.2	292.6
Rasht	279.6	278.9	281.8	287.1	291.7	295.5	298	297.7	295.0	290.0	285.4	281.9
Yazd	278.8	281	286.3	292.2	297.4	302.5	304.3	302.3	298.1	292.4	284.9	280.5

Table 6

Actual efficiency of the Stirling engine installed in the selected cities.

City	η_{real}											
	January	February	March	April	May	June	July	August	September	October	November	December
Tehran	0.29	0.32	0.33	0.34	0.34	0.34	0.34	0.33	0.32	0.31	0.28	0.27
Tabriz	0.28	0.32	0.33	0.34	0.34	0.34	0.34	0.33	0.32	0.30	0.28	0.26
Bandar Abbas	0.31	0.33	0.34	0.34	0.34	0.34	0.34	0.34	0.33	0.32	0.30	0.30
Rasht	0.28	0.31	0.33	0.34	0.34	0.34	0.34	0.33	0.32	0.30	0.27	0.26
Yazd	0.30	0.33	0.34	0.34	0.34	0.34	0.34	0.34	0.33	0.32	0.30	0.29

Table 7

Monthly number of hours with solar irradiation.

City	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Tehran	173.6	182.8	205.5	222.8	289.5	345.1	349.5	340.3	304.0	256.1	194.9	166.1	3030.2
Tabriz	123.5	146.1	179.5	201.3	269.5	336.7	353.6	339.5	303.3	231.8	177.3	132.2	2794.3
Bandar Abbas	221.9	210.7	225.4	254.9	312.8	307.6	271.8	271.2	265	281.9	251.8	226.2	3101.2
Rasht	91.7	89.2	89.9	123.6	174.0	209.7	220.5	180.3	137.7	118.7	96.3	89.1	1620.7
Yazd	190.3	210.6	218.9	242.9	300.7	343.5	345.7	345.0	316.0	286.4	224.2	199.0	3223.2

In the equations given in Table 10, $\dot{m}$, h , $\dot{E}$ and $\dot{Q}$ are mass flow rate (kg s^{-1}), specific enthalpy ($\text{kJ kg}^{-1} \text{K}^{-1}$), electric power consumption by the HVAC equipment (kW) and thermal capacity of

the HVAC equipment (kW), respectively. Furthermore, in Table 10, η and COP denote thermal efficiency and coefficient of performance for heating and cooling equipment, respectively.

Table 8

General specifications of the dish Stirling engine installed in the selected cities.

City	Electrical output capacity of the solar dish Stirling engine (kW) ^a			Dish diameter (m)		
	Scenario I	Scenario II	Scenario III	Scenario I	Scenario II	Scenario III
Tehran	4.00	5.84	10.00	5.05	6.10	8.00
Tabriz	3.58	4.70	10.00	4.72	5.50	8.00
Bandar Abbas	8.00	9.60	9.05	10.00	7.50	7.34
Rasht	7.97	5.67	10.00	6.98	6.02	8.00
Yazd	3.80	5.36	10.00	4.88	5.86	8.00

^a Electric output capacity of the solar dish Stirling engine is presented based on its output at maximum solar irradiation flux of 1000 W m⁻² for all the scenarios.

3.4. Evaluation of the primary energy saving (PES)

In order to estimate primary energy saving (PES) when the solar dish Stirling technology was used as a prime mover of the residential micro-CHP system, the primary energy consumption (PEC) of the proposed plant was compared with a residential building which utilized conventional HVAC system consuming electric and natural gas energy in order to follow up the same loads' profiles for that building. In this regard, a factor called source-site ratio (SSR) was utilized as introduced in the following sections.

3.4.1. Calculation of electricity and natural gas source-site ratios

In order to assess the primary energy consumption, it is essential to have source-site energy conversion ratios. These ratios were defined and taken into account for the electricity and natural gas consumption in this study.

According to EPA report [20], the electricity source-site ratio (ESSR) is calculated as the total primary energy involved in the electricity generation divided by the net generation minus transmission and distribution (T&D) losses. This calculation is summarized in Table 11. The annual values for the primary energy consumption for the power generation, net generation and T&D losses were extracted from the Iran Energy Bulletin and Iran energy flowcharts [16,17].

The source-site ratio for the natural gas (NGSSR) was obtained first by computing sum of natural gas delivered to consumers, pipeline, distribution use and plant use and then by dividing the result by the total delivery to consumers [20]. The calculated values for the natural gas source-site ratios are summarized in Table 12.

Table 9

Input data of the simulation.

Description	Symbol	Mean value
Boiler efficiency	η_b	0.90
Absorption chiller's coefficient of performance	COP_{ch}	0.70
Heat exchangers efficiency	$\eta_{H,E}$	0.75
Cooling coil efficiency	η_{cc}	0.80
Heating coil efficiency	η_{hc}	0.80

Table 10

Energy balance equations for the entire micro-CHP plant with solar dish Stirling engine.

Equation number	Energy balance equation
1	$\dot{m}_7 \cdot (h_{12} - h_7) - \dot{Q}_{cc} = 0$
2	$\dot{Q}_{cc} - COP_{ch} \cdot \dot{Q}_{ch} = 0$
3	$\dot{Q}_c - \eta_{cc} \cdot \dot{Q}_{cc} = 0$
4	$\dot{m}_{11} \cdot (h_{11} - h_{14}) - \dot{Q}_{hc} = 0$
5	$\dot{Q}_h - \eta_{hc} \cdot \dot{Q}_{hc} = 0$
6	$\dot{Q}_b - \dot{f}_b \eta_b = 0$
7	$\dot{m}_5 \cdot (h_5 - h_{13}) - \dot{Q}_{ch} = 0$
8	$\dot{m}_{20} \cdot (h_{20} - h_{22}) + \dot{m}_6 \cdot (h_6 - h_{12}) - \dot{Q}_{ch} - \dot{E}_{ch} = 0$
9	$\dot{m}_{11} \cdot (h_{11} - h_{15}) + \dot{m}_{16} \cdot (h_{16} - h_{10}) + \dot{Q}_{LS,H,E1} = 0$
10	$\dot{m}_{26} \cdot (h_{26} - h_{25}) + \dot{m}_{28} \cdot (h_{28} - h_{27}) + \dot{Q}_{LS,DWH1} = 0$
11	$\dot{m}_9 \cdot (h_9 - h_8) + \dot{m}_{29} \cdot (h_{29} - h_{28}) + \dot{Q}_{LS,DWH2} = 0$
12	$\dot{Q}_b - \dot{m}_3 \cdot (h_3 - h_{19}) = 0$
13	$\dot{Q}_b + \dot{m}_{23} \cdot h_{23} - \dot{m}_1 \cdot h_1 - \dot{m}_2 \cdot h_2 + \dot{Q}_{LS,b} - \dot{E}_b = 0$
14	$\dot{Q}_{LS,E} \cdot \eta_{H,E2} - \dot{m}_{24} \cdot (h_{24} - h_{26}) = 0$
15	$\dot{Q}_{hw} - \dot{m}_{27} \cdot (h_{30} - h_{27}) = 0$
16	$\dot{Q}_r - \dot{m}_{27} \cdot (h_{28} - h_{27}) = 0$
17	$\dot{Q}_{rec} = \dot{Q}_{sun,irr} \cdot A \cdot RF \cdot HLF$
18	$\dot{Q}_{hw} - \dot{Q}_r - \dot{m}_{28} \cdot (h_{30} - h_{28}) = 0$

Heat losses from surface of heat exchanger were assumed to be 1% of exchanger's heat duty. For the boiler, it was assumed to be 2% of the boiler capacity.

3.4.2. Analysis of the plant based on primary energy consumption

The primary energy consumption for the micro-CHP solar dish Stirling system ($PEC_{CHP-Solar}$) was:

$$PEC_{CHP-Solar} = (\dot{E}_{req} - \dot{E}_{SE}) \cdot ESSR + \left(\left(\frac{\dot{Q}_{hws}}{\eta_{hws}} \right) - \dot{Q}_r + \dot{Q}_{ch} + \left(\frac{\dot{Q}_{hc}}{\eta_{H,E1}} \right) \right) \cdot NGSSR \quad (7)$$

where η_{hws} and $\eta_{H,E1}$ are hot water system efficiency and efficiency of heat exchanger #1 (indicated in Table 9), respectively. ESSR and

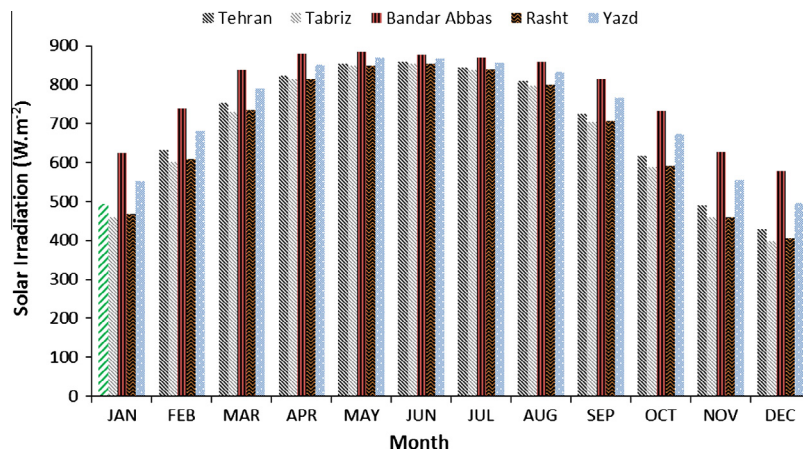
**Fig. 6.** Monthly solar irradiation ($Q_{solar,irr}$) for the selected cities.

Table 11
Electricity source– site ratios.

Year	PEC ^a for power generation (GW h) [21,22]	Net generation (GWh) [21,22]	T&D ^b loss (GW h) [21,22]	SSR ^c
2003	416168.03	142942.87	26575.41	3.570
2004	460129.44	159739.57	30341.77	3.550
2005	499531.89	170252.98	33086.72	3.640
2006	N.A	184589.16	32747.60	N.A
2007	523629.26	196030.74	45114.98	3.470
2008	592502.13	206163.71	45518.69	3.680
2009	610282.08	212960.05	43005.63	3.590
Average (2003–2009)				3.580

^a Primary energy consumption.^b Ransmission and distribution.^c Source-site ratio.**Table 12**
Natural gas source-site ratio.

Year	Some of pipeline, distribution use, plant fuel and delivery to consumers [20] (MBOE ^a)	Delivery to consumers [20] (MBOE)	Source-site ratio
2003	546.20	334.00	1.635
2004	615.10	387.10	1.612
2005	677.60	427.00	1.580
2006	N.A	N.A	N.A
2007	777.80	471.80	1.648
2008	820.20	476.50	1.720
2009	859.90	519.70	1.650
Average (2003–2009)			1.640

^a MOBE: Million barrel oil equivalent.

NGSSR denote electricity and natural gas source-site ratios, respectively. It is required to mention that, in the case that the electricity demand was less than the output capacity of the engine, the excessive electricity was sold to the local grid. Therefore, in such a case, $(\dot{E}_{req} - \dot{E}_{SE})$ was negative and caused reduction from the primary energy consumption ($PEC_{CHP-Solar}$).

Furthermore, the primary energy consumption for the reference building with conventional HVAC system PEC_{ref} was:

$$PEC_{ref} = (\dot{E}_{req}) \cdot ESSR + \left[\left(\frac{\dot{Q}_{hws}}{\eta_{hws}} \right) + \dot{Q}_{ch} + \left(\frac{\dot{Q}_{hc}}{\eta_{H.E1}} \right) \right] \cdot NGSSR \quad (8)$$

Then, the primary energy saving (PES) in the case of using micro-CHP solar Stirling system was:

$$PES = PEC_{ref} - PEC_{CHP-Solar} \quad (9)$$

3.5. Evaluation of carbon dioxide emission (CDE)

Electricity and natural gas emission factors were required for evaluating carbon dioxide emission for the proposed system. These values could be obtained from [23] as reflected in Table 13. For simplification purposes, it should be mentioned that these factors were considered the same in all the evaluated locations.

In order to show the environmental protection effect of the proposed system, it was compared with the reference building, which utilized a similar conventional HVAC system. To this end, carbon dioxide emissions from the CHP-solar Stirling system ($CDE_{CHP-Solar}$) were formulated as follows:

$$CDE_{CHP-Solar} = (\dot{E}_{req} - \dot{E}_{SE}) \cdot CDEF_E + \left[\left(\frac{\dot{Q}_{hws}}{\eta_{hws}} \right) - \dot{Q}_r + \dot{Q}_{ch} + \left(\frac{\dot{Q}_{hc}}{\eta_{H.E1}} \right) \right] \cdot CDEF_{NG} \quad (10)$$

Table 13

Conversion factor of carbon dioxide emissions for the electricity and natural gas and energy price [23,31,32].

Energy carrier	Conversion factor carbon dioxide emissions	Purchased cost of the energy	Sold price of the energy
Electricity	0.598 kg kW h ⁻¹	0.0150US \$ kW h ⁻¹	0.4200US \$ kW h ⁻¹
Natural gas	0.185 kg kW h ⁻¹	0.0126US \$ kW h ⁻¹	N.A

where $CDEF_E$ and $CDEF_{NG}$ denote carbon dioxide emission factors for the electricity and natural gas, respectively. Also, the carbon dioxide emission for the reference building can be obtained as follows:

$$CDE_{ref} = (\dot{E}_{req}) \cdot CDEF_E + \left[\left(\frac{\dot{Q}_{hws}}{\eta_{hws}} \right) + \dot{Q}_{ch} + \left(\frac{\dot{Q}_{hc}}{\eta_{H.E1}} \right) \right] \cdot CDEF_{NG} \quad (11)$$

Therefore, value of the carbon dioxide emission reduction (CDER) can be determined as:

$$CDER = CDE_{ref} - CDE_{CHP-Solar} \quad (12)$$

The CDER parameter showed the amount of carbon dioxide emission which was diminished on account of using the micro-CHP solar Stirling system in comparison to the reference conventional residential building.

3.6. Economic analysis

In this section, associated cost of the system capital investment for the solar dish Stirling system was compared with saving in the cost of primary energy consumption. In this regard, difference between capital investments of the micro-CHP system and reference building was divided by the saving in the cost of primary energy saving in order to estimate payback period for each location (five cities in this study). The economic analysis of this research was performed based on the total revenue requirement method. This method was developed based on the procedures adopted from the report of Electric Power Research Institute (EPRI; 1993) [24], refined and presented by Bejan et al. [25].

The annual total revenue requirement (TRR, total product cost) for a system is the revenue that must be collected in a given year by selling all products to compensate for the system operating company's all expenditure incurred in the same year and to ensure sound economic system operation [25]. It consists of two parts: carrying charges and expenses. Carrying charges are a general designation for charges that are related to the capital investment whereas expenses are used to define costs associated with the operation of a system. Examples for expenses are fuel cost (FC) and operating and maintenance costs (OMC) [25]. The series of annual costs associated with the carrying charges (CC_j) and expenses (FC_j and OMC_j) for the j th year of the system operation is not uniform. In general, carrying charges decrease while fuel costs increase with increasing years of operation. Therefore, in economic analysis of the proposed micro-CHP system, levelized values for costs namely CC_L , FC_L , OMC_L and TRR_L were used. In this analysis, the payback period for additional investment of the micro-CHP system (compared to the reference building) denoted as PBP was obtained using the levelized total revenue requirement (TRR_L), levelized cost of energy saving (CES_L), levelized income from electricity sold to the local grid (IES_L) and levelized reduction in the associated social cost for carbon dioxide ($CDERC_L$) from the following expression:

$$PBP = \frac{TRR_L}{CES_L + IES_L + CDERC_L} \quad (13)$$

Procedures for the estimation of TRR_L , CES_L , IES_L and $CDERC_L$ are presented in the following sections.

3.6.1. Calculation of total levelized revenue requirement, TRR_L

According to the procedure given in [25], the levelized total revenue requirement of an energy system was obtained. In this paper, this procedure was employed and adjusted based on feature of the proposed micro-CHP system. It should be noted that tax and insurance rates were ignored in this economic analysis as these economic parameters were not significant or existed for small energy systems. For the levelized total revenue requirement, the following can be given [25],

$$TRR_L = CRF \left(\frac{k(1 - k^{BL})}{1 - k} \right) \left(\sum_{j=1}^{BL} \frac{TRR_j}{(1 + i_{eff})^j} \right) \quad (14)$$

where CRF is capital recovery factor obtained from the following expression [19]:

$$CRF = \frac{i_{eff}(1 + i_{eff})^{BL}}{(1 + i_{eff})^{BL} - 1} \quad (15)$$

In Eqs. (14) and (15), i_{eff} and BL are effective interest rates (assumed as 12%) and booked life of the micro-CHP system (assumed as 20 years), respectively. In Eq. (14), k is a factor obtained from inflation rate (escalation factor), r (assumed as 6%) and effective interest rate (i_{eff}) as follows [20],

$$k = \frac{1 + r}{1 + i_{eff}} \quad (16)$$

TRR_j is the total revenue requirement associated to the additional investment of the micro-CHP system (compared to investment of the reference building) for the j th year of the system operation. TRR_j for the solar dish Stirling micro-CHP system is simplified and calculated from the following expression,

$$TRR_j = TCR_j + ROI_j + OMC_j \quad (17)$$

where TCR_j , ROI_j and OMC_j are total capital recovery, return on investment and operating and maintenance costs for j th year of the system operation, respectively. These parameters were determined based on the procedure given in following sections.

3.6.1.1. Calculating total capital recovery, TCR_j . TCR_j is obtained based on the total depreciable investment (TDI) and booked life of the system ($BL = 20$) as follows (from [25], with slight modification),

$$TCR_j = \frac{TDI}{BL} \text{ for } j = 1, 2, \dots, BL \quad (18)$$

3.6.1.2. Calculating return on Investment, ROI_j . Return on investment for j th year of the system operation ROI_j was obtained based on expression given in [25] with slight modification as follows,

$$ROI_j = BBY_j \cdot i \text{ for } j = 1, 2, \dots, BL \quad (19)$$

where BBY_j is the balance at the beginning of the j th year and i is the annual rate of return for investment, which was assumed 15% in this study. With slight modification from [25], the following can be written

$$BBY_{j,x} = \begin{cases} TNI & \text{for } j = 1 \\ BBY_{j-1} - \frac{TDI}{BL} & \text{for } j = 2, 3, \dots, BL \end{cases} \quad (20)$$

where TNI and TDI are total net investment and total depreciable investment, respectively. For simplicity, it was assumed that total net investment was depreciated in booked life of the system; therefore: $TDI = TNI$.

Calculation procedure for TNI of large energy systems is complicated and is obtained from several investment parameters as presented in [25]. Fortunately, the present system was a small energy system and its investment was simply composed of the purchased equipment cost, engineering and construction cost, contingency and other costs. Other components of the total net investment such as start-up cost, piping and instrument cost, engineering cost, land cost and so on were not significant or not exist in the case of the micro-CHP system. Therefore, only the additional cost which was invested to purchase and employ the solar dish Stirling system was considered here. Total purchased equipment cost (TPC) was composed of the purchased cost of the solar dish (including collector and receiver), free piston Stirling engine, heat exchanger#2 and domestic hot water heater#1 (D.W.H.1 was used to recover the rejected heat from the cold end of the Stirling engine-see Fig. 1). Furthermore, when D.W.H.1 was employed in the CHP system, it reduced the required heating capacity of the hot water boiler; hence, a cheaper hot water boiler should be purchased. Therefore, difference between the purchased cost of the hot water boiler of the reference building and that of micro-CHP system should be considered in calculation of the total purchased cost of CHP equipment (TPC). Thus,

$$TPC = C_{COLEC} + C_{RESIV} + C_{SE} + C_{H.E2} + (C_{b,REF} - C_{b,CHP}) \quad (21)$$

C_{COLEC} , C_{RESIV} , C_{SE} , $C_{H.E2}$, $C_{b,REF}$ and $C_{b,CHP}$ are purchase equipment costs for solar collector, solar receiver, free piston Stirling engine, heat exchanger #2, hot water boiler used in the reference building and hot water boiler used in the CHP system, respectively. These data were obtained from vendor price list of the equipment.

$$C_{COLEC} = 400A_{COLEC} \text{ US \$} \quad (22a)$$

$$C_{RESIV} = 0.250(DNI) \text{ US \$} \quad (22b)$$

$$C_{SE} = 500.W_{SE} \text{ US \$} \quad (22c)$$

$$C_{H.E2} = 6.1745Q_{H.E} + 134.5 \text{ US \$} \quad (22d)$$

$$C_b = 10.43Q_b + 94.572 \text{ US \$} \quad (22e)$$

where $Q_{H.E}$ and Q_b are the heat duty of heat exchanger (kW) and heating capacity of the hot water boiler (kW), respectively. Contingency, piping and installation and other costs were considered 10%, 16% and 3% of the total purchased cost of equipments (TPC); therefore, for total net investment, the following can be assumed

$$TNI = 1.29TPC \quad (23)$$

3.6.1.3. Calculating Operating and Maintenance Cost, OMC_j . In this section, the procedure for evaluating annual cost of operating and maintenance for j th year of the system operation is presented. Since additional cost of the micro-CHP system was to be compared with the reference building using conventional HVAC system, only the associated operating and maintenance cost of the dish Stirling part was considered in this analysis. Based on the expression given in [25], operating and maintenance cost of a system for j th year of the system operation could be obtained as,

$$OMC_j = \left(\frac{k_{OMC}(1 - k_{OMC}^j)}{1 - k_{OMC}} \right) \cdot OMC_1 \text{ for } j = 2, 3, \dots, BL \quad (24)$$

where OMC_1 is the operating and maintenance cost in the first year of the system operation. It is assumed to be 5% of purchased cost for the CHP equipment. k_{OMC} is a factor that is obtained from the similar expression to Eq. (16) but with corresponding escalation factor for the cost of operating and maintenance, r_{OMC} (assumed as 5%).

3.6.2. Calculating levelized cost of energy saving, CES_L

The levelized cost of energy saving was evaluated based on the magnitude of primary energy saving and levelized energy price (fuel cost) for each energy carrier including natural gas and electricity. Therefore,

$$CES_L = FC_{LNG} + FC_{LE} \quad (25)$$

where FC_{LNG} and FC_{LE} are levelized annual fuel cost (energy price) of natural gas and electricity, respectively. The levelized fuel cost for each energy carrier including natural gas and electricity was defined as [25],

$$FC_L = CRF \cdot \left(\frac{k_{FC}(1 - k_{FC}^{BL})}{(1 - k_{FC})} \right) \cdot FC_1 \quad (26)$$

where k_{FC} is a factor that is obtained from the similar expression to Eq. (16) but with corresponding escalation factor for the cost of fuel cost, r_{FC} (assumed as 6%). FC_1 is annual fuel cost in the first year of the system operation, evaluated from the following expression,

$$FC_1 = (c_{fNG} \cdot PES_{NG}) + (c_{fE} \cdot PES_E) \quad (27)$$

where PES_{NG} and PES_E are primary energy saving for natural gas and electricity and c_{fNG} and c_{fE} are unit costs of natural gas and electricity, respectively. These unit costs were evaluated based on OECD countries' market as 0.0126\$ kW h⁻¹ and 0.015\$ kW h⁻¹ for natural gas and electricity, respectively, as presented in Table 13.

3.6.3. Calculating levelized income from energy sold to local grid, IES_L

The proposed dish Stirling system had flexibility to buy and sell electric energy from/to the local grid. As mentioned previously, when the output capacity of the solar dish Stirling engine was lower than the total electric demand, difference between the actual demand and power generation was provided by local grid. On the contrary, when electricity demand was lower than the output power, the excessive electric energy was sold to the local grid. Therefore, in this case, there was income from the electricity purchased to the grid. In calculation of the system payback period, the levelized value for this income should be evaluated as predicted in Eq. (13). For IES_L , the following can be given,

$$IES_L = CRF \cdot \left(\frac{k_E(1 - k_E^{BL})}{(1 - k_E)} \right) \cdot IES_1 \quad (28)$$

where k_E is a factor obtained from the similar expression to Eq. (16) but with corresponding escalation factor for the cost of electricity, r_E (assumed 6%). IES_1 is the annual income from electric energy sold to the local grid in the first year of the system operation evaluated from the following expression,

$$IES_1 = c_E \cdot EESG \quad (29)$$

where c_E and $EESG$ are unit costs of electric energy sold to the grid (assumed as 0.02US\$ kW h⁻¹) and annual electric energy sold to the grid in kW h, respectively. For $EESG$, the following can be given,

$$EESG = \int_0^{8760h} \dot{E}_{sold} \cdot dt \quad (30)$$

where $\dot{E}_{sold}$ is obtained from Eq. (3b).

3.6.4. Calculating levelized carbon dioxide emission reduction cost, $CDERC_L$

Carbon dioxide emission imposes the social cost associated with health and environmental expenditure. When the solar dish Stirling CHP is implemented, due to reduction in greenhouse gas emission, there is a kind of monetary saving in the social scale. In calculation of the payback period for return of investment of the CHP system, such a kind of monetary saving should be consid-

ered as predicted by Eq. (13). Therefore, a levelized value for the associated cost of carbon dioxide emission reduction ($CDERC_L$) is calculated as follows,

$$CDERC_L = CRF \cdot \left(\frac{k_{CDERC}(1 - k_{CDERC}^{BL})}{(1 - k_{CDERC})} \right) \cdot CDERC_1 \quad (31)$$

where k_{CDERC} is a factor obtained from the similar expression to Eq. (16) but with corresponding escalation factor for the cost of electricity, r_{CDERC} (assumed as 6%). $CDERC_1$ is the annual cost associated with carbon dioxide emission reduction in the first year of the system operation. $CDERC_1$ is evaluated from the following expression,

$$CDERC_1 = c_{env} \cdot CDER \quad (32)$$

where $CDER$ is annual reduction of the carbon dioxide emission as evaluated in Section 3.5. c_{env} is the environmental cost associated with each kilogram of the carbon dioxide emission. In this paper, it was considered to be 0.02086 \$ kg⁻¹ [26–28].

4. Methods

As mentioned previously, three scenarios were considered in analyzing the proposed dish Stirling micro-CHP system. First of all, the proposed system as shown in Fig. 1 was analyzed in five cities with diverse climatic conditions based on the first law of thermodynamic using the method mentioned in Sections 3.1–3.3. Therefore, load estimations, material and energy balance (as in Table 10), first law analysis of the solar dish Stirling engine and finally first law analysis of the entire system were performed in this step.

In the second step, the primary energy saving, reduction on carbon dioxide emission and payback period for additional investment of the CHP system were analyzed and compared to the reference building with conventional HVAC system in the aforementioned five locations. In this section, the proposed CHP system was analyzed based on the models presented in Sections 3.4–3.6. Therefore, values of the annual primary energy saving (PES), annual carbon dioxide emission reduction ($CDER$) and payback period (PBP) for each scenario were obtained for each location.

In the third step, PES , $CDER$ and PBP were considered three key criteria for selection and sizing of the suitable CHP system in each site. In this regard, for each city, a proper scenario for decision making on the size of the solar dish Stirling engine was introduced by a process of decision making, in which PES , $CDER$ and PBP were criteria of decision making. In this case, decision making was performed using the TOPSIS decision making method. The ideal optimal configuration is obtained in a scenario having maximum PES , maximum $CDER$ and minimum PBP . It is clear that each scenario might have better values for some criteria but worse values for other criteria as PES , $CDER$ and PBP were conflicting criteria. The ideal scenario had minimum values for payback period (PBP_{ideal}) and maximum values for the carbon dioxide emission reduction and primary energy saving ($CDER_{ideal}$ and PES_{ideal}) among three scenarios. The worst scenario was a scenario with maximum values for payback period ($PBP_{non-ideal}$) and minimum values for the carbon dioxide emission reduction and primary energy saving ($CDER_{non-ideal}$ and $PES_{non-ideal}$). In the TOPSIS decision making [29,30], deviation of each scenario from the ideal and non-ideal scenarios was evaluated and a proper scenario with minimum deviation from the ideal scenario and maximum deviation from the non-ideal solution was introduced. In the following section, basics of TOPSIS decision making are introduced.

4.1. Decision making

In a multi-criteria problem, a process of decision making is required for selecting the desired option from available options. There are several methods for decision making process. Since dimension of various criteria in a multi-criteria problem might be different, prior to any decision making, dimensions and scales of criteria should be unified. In this regard, criteria vectors should be non-dimensionalized before decision making. There are some methods of non-dimensionalization utilized in decision making including linear non-dimensionalization, Euclidian non-dimensionalization and fuzzy non-dimensionalization. As Euclidian non-dimensionalization was employed in TOPSIS method [29,30], Euclidian non-dimensionalization is discussed as follows,

4.1.1. Euclidian non-dimensionalization

In this method, a non-dimensionalized criterion, F_i^n , is defined as,

$$F_i^n = \frac{F_i}{\sqrt{\sum_{i=1}^m (F_i)^2}} \quad (33)$$

where F_i denotes value of each criteria ($F_1 = PES$, $F_2 = CDER$ and $F_3 = PBP$) and m is total number of criteria ($m = 3$ in this study).

4.2. TOPSIS decision making method

An ideal solution is the solution with the best value for each criterion and the non-ideal solution has the worst value for each criterion among the values obtained for that criterion in all options (scenarios in this study). It is obvious that, in the multi-criteria problem with conflicting criteria as in the present study's case, it is impossible for any scenario to have the best values for all the criteria. Therefore, the ideal option (scenario) does not exist in real world. In the TOPSIS method, after Euclidian non-dimensionalization of all the criteria, an ideal criterion and a non-ideal criterion are specified through comparison of values of each criteria (F_i) for all scenarios. Therefore, the best values of all the criteria are dedicated to the ideal solution ($F_{i,ideal}$) and the worst values are dedicated to the non-ideal solution ($F_{i,non-ideal}$). Then, all the criteria are non-dimensionalized based on Eq. (30) and special distances from the ideal and non-ideal solutions denoted by d_i^+ and d_i^- in the non-dimensionalized criteria space are determined as follows,

$$d_i^+ = \sqrt{\sum_{i=1}^m (F_i^n - F_{i,ideal}^n)^2} \quad (34a)$$

$$d_i^- = \sqrt{\sum_{i=1}^m (F_i^n - F_{i,non-ideal}^n)^2} \quad (34b)$$

where m denotes number of criteria. In continuing the TOPSIS method, a parameter denoted by c_i can be defined as follows,

$$c_i = \frac{d_i^-}{d_i^+ + d_i^-} \quad (35)$$

In TOPSIS method, a solution with maximum c_i is selected as a desired final solution; therefore, if i_{final} is an index for the final selected solution, then,

$$i_{final} \equiv i \in \max(c_i) i = 1, 2, \dots, m \quad (36)$$

5. Results and discussion

5.1. Monthly variation of key parameters

Figs. 7–10 illustrate monthly variations of the Stirling engine's electric efficiency, overall efficiency of the solar dish Stirling CHP system, primary energy saving (PES) and carbon dioxide emissions reduction (CDER) for Scenario I (sizing of the primary mover based on the minimum annual electricity demand) at various locations, respectively. Fig. 7 demonstrates monthly variation of thermal efficiency of the solar Stirling engine (Scenario I). It indicates that maximum thermal efficiency of the solar Stirling engine was 34.5% obtained in Tabriz in May. On the other hand, minimum efficiency was 25.9% in Rasht in December. These values could be attributed to the variation of direct normal solar irradiation which was at the highest level in summer and the lowest level in winter. Moreover, low ambient temperature in Tabriz caused higher Carnot efficiency and subsequently more real electric efficiency.

Fig. 8 represents monthly variation of the overall energy efficiency of the micro-CHP system for the system sized based on Scenario I. The highest and lowest efficiency rates were 78.4% and 53.1%, which were associated with Tabriz in March and Bandar Abbas in August, respectively. Considering Eqs. (16) and (18) presented in Table 10, since the maximum heat recovery (Q_r) occurred in cold months, it is anticipated to have the maximum efficiency in these months. On account of having the lowest hot water demand and consequently the lowest heat recovery in Bandar Abbas, it can be predicted that the minimum overall efficiency can be obtained in this city.

Fig. 9 demonstrates percentage of primary energy saving (PES) for the solar dish Stirling CHP system in comparison to the reference building that did not utilize the CHP system. The PES percentage highly depends on four factors: solar direct normal irradiation,

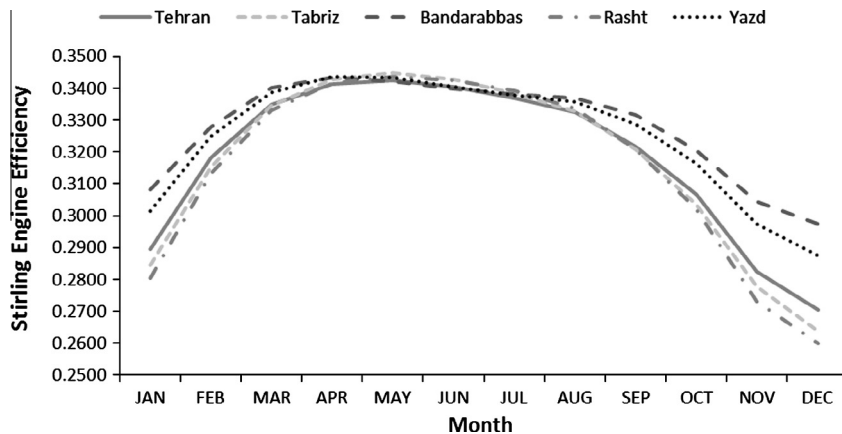


Fig. 7. Monthly Stirling engine efficiency for the selected cities.

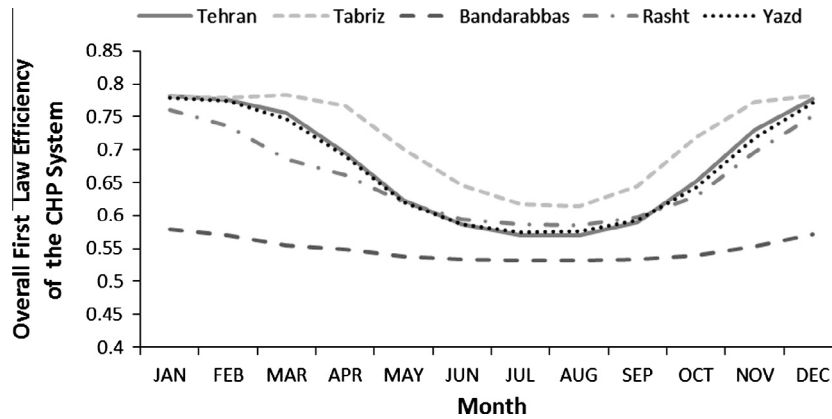


Fig. 8. Monthly overall energy efficiency of the CHP-solar Stirling system for the selected cities.

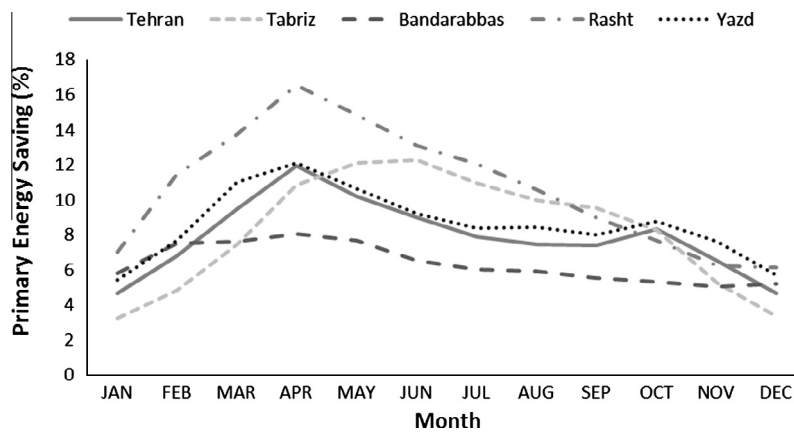


Fig. 9. Monthly primary energy saving percentage for the selected cities.

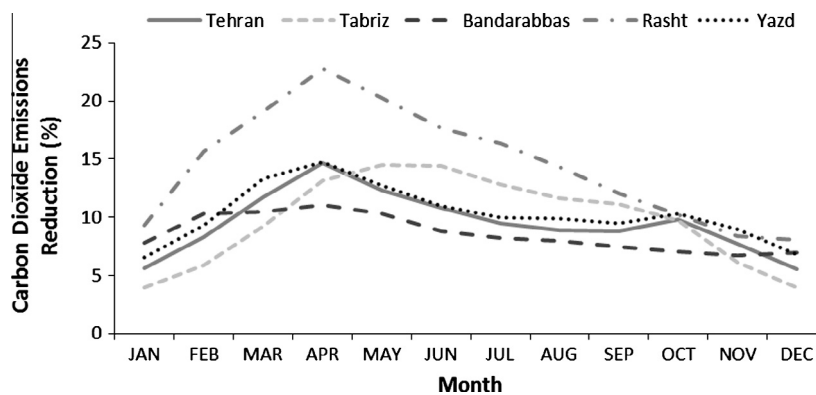


Fig. 10. Monthly percentage of carbon dioxide emissions reduction for the selected cities.

ambient temperature, number of hours with solar radiation per day and excess electricity produced by the Stirling engine. However, the most prevalent factor is the solar direct normal irradiation. As shown in Fig. 9, the maximum primary energy saving (16.53% in April) was acquired in the case that this CHP system was utilized in Rasht since the excessive electricity produced by the Stirling engine ($\dot{E}_{ex}$) in this location was the highest among other locations, which led to higher primary energy saving. It is essential to mention that the minimum primary energy saving

was associated to Tabriz in January with value of 3.25% which was influenced by four cited factors.

Fig. 10 illustrates monthly variation of the percentage of carbon dioxide emission reduction which was gained when the solar dish Stirling system CHP (Scenario I) was utilized. Similar to the trend of the PES variation, maximum and minimum percentage of carbon dioxide emissions reduction belonged to Rasht in April and Tabriz in January, respectively (22.8% and 3.9%). It can be concluded that the variation trend of carbon dioxide emission reduction was

similar to that of the primary energy saving because emission of carbon dioxide was almost influenced by consumption of electricity and natural gas in the site, amount of heat recovery from the Stirling engine and amount of electric energy sold to the grid.

5.2. Annual values of key parameters

Figs. 11–15 demonstrate annual values of the average thermal efficiency of the Stirling engine, average overall efficiency of the solar dish Stirling CHP system, primary energy saving (PES), carbon dioxide emissions reduction and values of the payback period presented in three scenarios for the selected locations, respectively. These data were presented in order to have better insights regarding overall operation of the proposed CHP system.

Fig. 11 shows average annual thermal efficiency of the Stirling engine efficiency obtained at different locations. Since thermal efficiency of the Stirling engine in this analysis did not depend on the size of engine, value of this efficiency at each site was the same in the three scenarios. Therefore, Fig. 11 does not separately show Scenarios I, II and III. The highest value of average annual efficiency of the Stirling engine efficiency belonged to Bandar Abbas (32.7%) and the lowest value was associated to Rasht (31.5%). On the account of considering the real engine efficiency as the percentage of Carnot efficiency in this study, it is anticipated that the most important factor affecting thermal efficiency could be difference

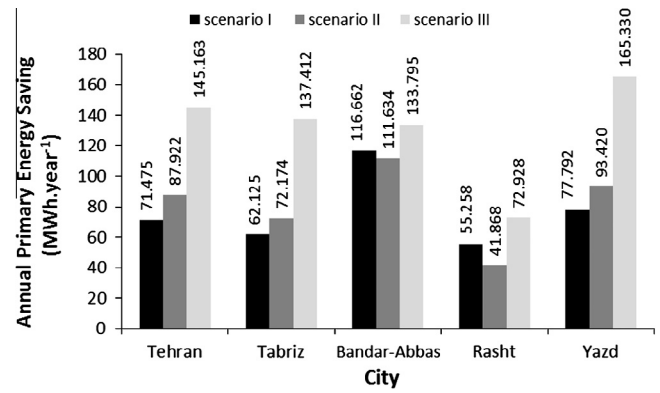


Fig. 13. Annual primary energy saving for the selected cities.

between the temperature of heat source and heat sink in Stirling engine operation. Therefore, due to having the maximum difference between these two temperatures in Bandar Abbas, it can be concluded that this city had the highest Stirling engine efficiency.

Average annual overall efficiency of the solar dish Stirling CHP system for three scenarios and five locations is presented in Fig. 12. This parameter depended on the series of factors such as energy demands of the proposed building, solar irradiation, output

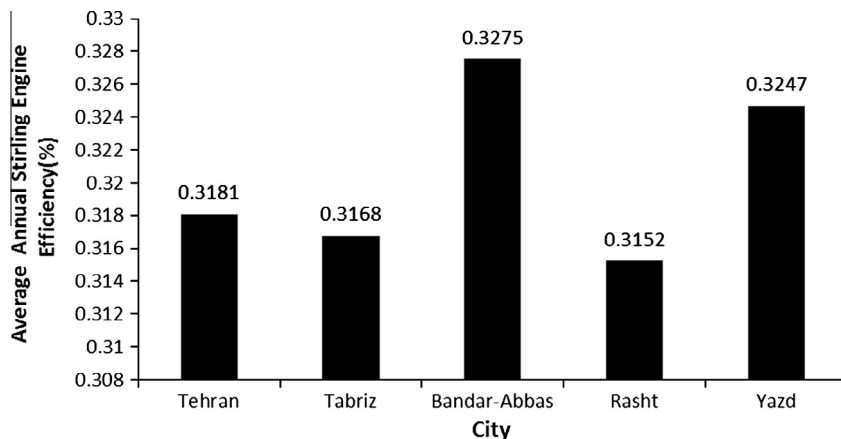


Fig. 11. Annual values of Stirling engine efficiency for the selected cities.

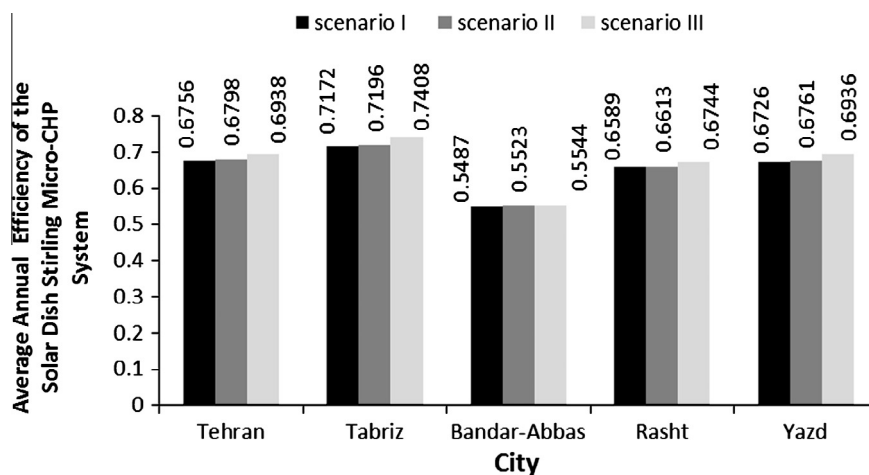


Fig. 12. Annual values of the overall efficiency of the CHP-Stirling system for the selected cities.

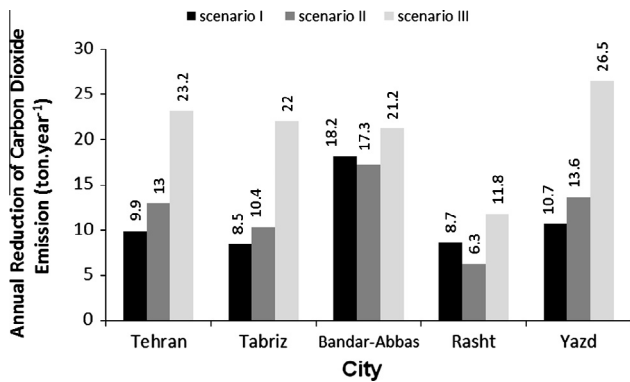


Fig. 14. Annual carbon dioxide emissions reduction for the selected cities.

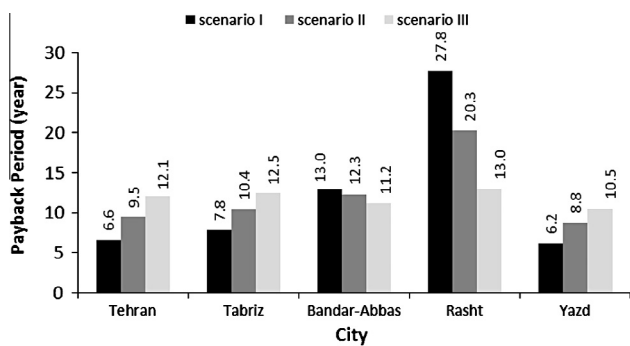


Fig. 15. Values of the payback period of different scenarios obtained for the selected cities.

electric power of the Stirling engine and amount of heat recovery at the cold-end of the Stirling engine. The figure shows that Tabriz had the maximum overall efficiency (71.7%, 71.96% and 74.08% for Scenarios I, II and III, respectively) among the selected locations. This could be due to the fact that, in Tabriz, the inlet tap water temperature to the D.W.H#1 was in the lowest value; therefore, this city had superior capability of absorbing the heat recovered from the cold-end of the solar Stirling engine. On the other side, due to a similar reason in Bandar Abbas with the highest inlet tap water to the D.W.H #1, the lowest average annual overall efficiency occurred (54.87%, 55.23% and 55.44% for Scenarios I, II and III, respectively). It should be cited that Tehran and Yazd had very little difference in the amount of system's overall efficiency (67.5% and 67.2%, respectively) because of being similar in the building energy demands, solar irradiation and amount of heat recovered in both cities.

Furthermore, Fig. 12 indicates that, in all the locations, the CHP system that was sized based on Scenario III had the highest value for the average overall thermal efficiency of the CHP system, which was for the sake of the fact that, in this scenario, size of Stirling system was higher than the corresponding size of the Stirling engine in Scenarios I and II. Therefore, by considering reduction of parameters in denominator of Eq. (4), the overall efficiency in Scenario III was higher than the corresponding overall efficiency in Scenarios I and II.

Fig. 13 illustrates total amount of annual primary energy saving for three scenarios and five locations. The primary energy saving for the presented system hinged on some factors such as amount of solar irradiation, annual number of hours with solar irradiation, amount of heat recovered from the cold-end of the Stirling engine and excessive electric power generated by the Stirling engine. The presented figure shows that the highest annual primary energy

saving belonged to Bandar Abbas. It revealed that, in Bandar Abbas, higher solar irradiation condition was more dominant and influential factor than the amount of heat recovered at the cold-end of the Stirling engine. The minimum annual primary energy saving was related to Rasht which had the worst annual solar irradiation condition among the proposed locations. Moreover, the mild outdoor winter design temperature in Rasht led to decreasing the amount of heat recovery in comparison to the cold cities. This is another reason for causing lower primary energy saving in Rasht in comparison to other locations. Furthermore, as is evident from Fig. 13, the highest primary energy saving was in Scenario III for all the locations, which was on the ground that, in Scenario III, there was a Stirling engine with greater capacity in comparison to other two scenarios for all the locations. Therefore, in Scenario III, there was lower purchased electric energy from the grid and lower natural gas consumption (because of higher heat recovery at the cold-end of engine); hence, PES was higher in this scenario.

Fig. 14 demonstrates annual amount of carbon dioxide emission reduction for three scenarios and five locations. As carbon dioxide emission was directly proportional to the amount of primary energy consumption, due to a similar reason to the previously expressed one for the PES, in terms of annual carbon dioxide emissions reduction among the selected cities, Rasht and Yazd had a lowest and greatest promising potentials in reducing the amount of carbon dioxide emission in Scenarios II and III respectively. In Scenario I, carbon dioxide emission reduction potential of Tabriz was a little lower than that of Rasht, due to having unfavorable solar irradiation in Tabriz as a result of the cloudy sky in most times of the year. In a similar trend to the primary energy saving, value of carbon dioxide emission reduction for Scenario III was greater than the corresponding values of Scenarios I and II for all the locations.

Figs. 13 and 14 reveal that, in terms of the primary energy saving and carbon dioxide emission reduction, Tabriz and Rasht were two similar worst cities which could be attributed to the similarity of direct normal solar irradiation, ambient temperature, electricity demand of the building and amount of power produced by the Stirling engine.

Payback period for additional investment of the solar dish Stirling CHP system as a very important factor for assessment of the proposed CHP system for three scenarios and five locations is presented in Fig. 15. According to the data presented in Fig. 15, it can be seen that Yazd had the best economic condition for utilization of the solar dish Stirling CHP system. Values of payback period for this city in Scenarios I, II and III were 6.2, 8.8 and 10.5 years, respectively. With respect to Eq. (13), the payback period depended on four factors including leveled values for the total revenue requirement (TRR_L), cost of energy saving (CES_L), income from electricity sold to the local grid (IES_L) and carbon dioxide emission reduction cost (CDE_{RC_L}). TRR_L was entirely affected by the cost of system (included investment and O&M costs) with respect to the reference building. Other three mentioned parameters were related to energy and environmental operation of the system. Therefore, in the case of having good solar irradiation in Yazd, it is expected to have one of the most primary energy saving costs and carbon dioxide emission reduction costs, which consequently causes the lowest payback period for this city. In the case of Rasht due to having the worst solar irradiation, the values of payback period for all three scenarios were much higher than other cities. It should be mentioned that, because of having undesirable solar irradiation in Rasht, higher size of dish Stirling system was required in order to cut down the value of payback period. This fact is clear as shown in Fig. 15 for Scenario III in Rasht. On the other side, sizing of the prime mover based on maximum annual electricity demand (Scenario II) in cities which had fairly good solar irradiation (Tehran, Tabriz and Yazd) led to increase in the value of

Table 14

Decision making based on the TOPSIS method for five locations.

Scenario	PES (MW h year ⁻¹)					CDER (Ton year ⁻¹)					Payback period (year)					c_i Index (TOPSIS)				
	Tehran	Tabriz	Bandar- abbas	Rasht	Yazd	Tehran	Tabriz	Bandar- abbas	Rasht	Yazd	Tehran	Tabriz	Bandar- abbas	Rasht	Yazd	Tehran	Tabriz	Bandar- abbas	Rasht	Yazd
I	71.5	62.1	116.7	55.3	77.8	9.9	8.5	18.2	8.7	10.7	6.6	7.8	13.0	27.8	6.2	0.622	0.621	0.425	0.388	0.623
II	87.9	72.2	111.6	41.9	93.4	13.0	10.4	17.3	6.3	13.6	9.5	10.4	12.3	20.3	8.8	0.499	0.529	0.453	0.406	0.510
III	145.2	137.4	133.8	72.9	165.3	23.2	22.0	21.2	11.8	26.5	12.1	12.5	11.2	13.0	10.5	0.227	0.219	0.397	0.546	0.225
Ideal	145.2	137.4	133.8	72.9	165.3	23.2	22.0	21.2	11.8	26.5	6.6	7.8	11.2	13.0	6.2	1.0	1.0	1.0	1.0	1.0
Non-ideal	71.5	62.1	111.6	41.9	77.8	9.9	8.5	17.3	6.3	10.7	12.1	12.5	13.0	27.8	10.5	0.0	0.0	0.0	0.0	0.0

Table 15

Final specifications of the selected solar dish Stirling micro-CHP systems at five locations.

Parameter	Tehran		Tabriz		Bandar Abbas		Rasht		Yazd	
	Actual value	Value per m ² of building	Actual value	Value per m ² of building	Actual value	Value per m ² of building	Actual value	Value per m ² of building	Actual value	Value per m ² of building
Output power (kW)	4.00	0.0040	3.58	0.0036	9.60	0.0096	8.00	0.0080	3.80	0.0038
Dish diameter (m)	5.05	0.0051	4.72	0.0047	7.5	0.0075	10.00	0.0010	4.88	0.0049
Annul average thermal efficiency of the Stirling engine (%)	31.81	N.A	31.68	N.A	32.75	N.A	31.52	N.A	32.47	N.A
Overall annual average efficiency of the CHP system (%)	67.56	N.A	71.72	N.A	55.23	N.A	67.44	N.A	67.26	N.A
Annual primary energy saving (MW h year ⁻¹)	71.475	0.0715	62.125	0.0621	111.634	0.1116	72.928	0.0729	77.792	0.0778
Annual carbon dioxide emission reduction (Ton year ⁻¹)	9.9	0.0099	8.5	0.0085	17.3	0.0173	11.8	0.0118	10.7	0.0107
Total net investment (US \$)	25510.0	25.510	22415.2	22.415	54569.9	54.570	103139	103.139	23950.0	23.950
Levelized total revenue requirement (TRR_L) (US \$)	1845.4	1.845	1621.5	1.622	3947.6	3.948	7461.2	7.461	1732.6	1.733
Levelized cost of energy saving (CES_L) (US \$)	124.5	0.124	107.5	0.108	204.3	0.204	136.6	0.137	135.1	0.135
Levelized income from electricity sold to the grid (IES_L) (US \$)	2.1	0.002	0.0	0.000	70.8	0.071	304.7	0.305	1.2	0.001
Levelized cost of carbon dioxide emission reduction ($CRERC_L$) (US \$)	26.2	0.026	22.4	0.022	45.6	0.046	31.2	0.031	28.3	0.028
Payback period (year)	6.6	N.A	7.8	N.A	12.3	N.A	13.0	N.A	6.2	N.A

payback period. In Tehran, Tabriz and Yazd, Scenario I was more desirable and Scenario III was the worst scenario from the viewpoint of the payback period. In Rasht and Bandar Abbas, the best scenario was Scenarios III and I was the worst one considering the payback period of the system investment. One common feature of these two cities is humid weather. Therefore, it can be said that, for cities with humid weather, Scenario III is a better option than the other two.

5.3. Specifying the best scenario for sizing solar dish Stirling micro-CHP system

In previous Sections 5.1 and 5.2, basic features of the proposed solar dish Stirling micro-CHP system were assessed based on key parameters of the system including thermal efficiencies, primary energy saving (PES), carbon dioxide emission reduction (CDER) and payback period (PBP) for additional investment of the CHP system. In this section, the best scenario for each location is suggested based on three criteria of PES, CDER and PBP. In this regard, ideal and non-ideal scenarios are defined based on the best and worst values of three criteria, as described in Section 4. Therefore, for each location, the best scenario was identified using the TOPSIS

decision making method, as described in Section 4.2. Table 14 represents values of three criteria for Scenarios I, II and III, both ideal and non-ideal, in five locations. Furthermore, this table shows c_i index (based on Eq. (35)) as used in TOPSIS decision making method) for each scenario and location. As in the TOPSIS method, an option with the highest value of c_i was desired (according to Eq. (36)); for each location, a scenario which had the highest c_i was selected as the desired scenario for sizing the micro-CHP system. The highest c_i index in Table 14 is specified by bold-underlined fonts. According to Table 14, the final recommended scenario for Tehran, Tabriz and Yazd was the system sized based on Scenario I (sized based on minimal annual electric power demand). For Bandar Abbas, Scenario II in which the system was sized based on the maximum annual value for electric power demand was recommended. For Rasht, a constant size of the solar Stirling system based on Scenario III was suggested by the TOPSIS decision maker.

Table 15 summarizes the finally suggested features of the solar dish Stirling micro-CHP system for each location. Furthermore, as value of the finally recommended system was presented for a specific building with 960 m² residential area in order to suggest some thumb rule values for other buildings, values of parameter per square meter of the building are also presented in Table 15.

6. Conclusion

This paper presented thermodynamic analysis of a CHP-solar dish Stirling engine which was integrated with a conventional HVAC system in order to provide a part of heating, hot water demand and electrical loads of a building including electric demand of HVAC equipment. Likewise, considerable reduction or even omission of the pollution emissions in power generation section of the presented system was a promising objective that could decrease the emissions produced by burning fossil fuels in power plants. Performance of the system was analyzed in diverse climatic conditions. In this regard, five cities in Iran including Tehran (with temperate and dry weather), Tabriz (with cold and dry weather), Bandar Abbas (with hot and humid weather), Rasht (with temperate and humid weather) and Yazd (with hot and dry weather) were considered. Among these cities, from the view point of overall energy efficiency, Tabriz had the highest overall efficiency but, in terms of annual primary energy saving, annual carbon dioxide emissions reduction and annual Stirling engine efficiency, Bandar Abbas had better performance. It was shown that this system had a great potential for reducing primary energy saving and carbon dioxide emission reduction. Economic analysis of the system indicated that, in Tehran, Tabriz and Yazd, the payback period for the investment of the CHP system was almost less than half of the system life cycle (in Scenario I, it was almost one third of the system life time). In Bandar Abbas, the payback period was a little greater than the half-life of the system. However, in Rasht, due to the great number of times with cloudy weather, the payback period was not acceptable for Scenarios I and II and the payback period was a little greater than the half-life of the system for Scenario III. Since economic criterion showed conflicting behaviors with the primary energy saving and carbon dioxide reduction criteria, the best system configuration was specified through a decision making tool called the TOPSIS decision-maker. It was shown that, in cities with dry weather such as Tehran, Tabriz and Yazd, the best scenario in sizing the solar dish Stirling system was Scenario I, in which the system was sized based on the minimum annual electric power demand. In Bandar Abbas with hot and humid weather, the best scenario was the scenario in which the system was sized based on the maximum annual electric power requirement (Scenario II). In Rasht with temperate and humid weather, the fixed size of the Stirling engine (Scenario III) was the best choice. This analysis showed a useful methodology and tool in energetic, environmental and economic assessment of each residential CHP or CCHP system and could be applied for assessment and size evaluation of the prime mover for the CHP or CCHP systems in each climatic and solar irradiation condition.

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